30th Congress of the International Council of the Aeronautical Sciences
DCC, Daejeon, Korea ; September 25-30, 2016

THE ANALYSIS OF LAMINATE LAY-UP EFFECT ON THE FLUTTER SPEED OF COMPOSITE STABILIZERS

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Keywords: *flutter, composites, missile stabilizer, aeroelasticity.*

Abstract

This paper presents an analytical study on the effect of laminate lay-up of composite missile stabilizer structure for achieving a maximum flutter speed without strength penalty.

The flexible stabilizer structure in high–velocity flow may experience flutter, an aeroelastic phenomena where vibrations of the structure become unstable and can cause stability loss and flight vehicle failure. Flutter in missiles is mainly affected by the aerodynamic and structural properties of the stabilizers whereas flight vehicle body has a minor role.

In the present paper the effect of laminate lay-up on flutter speed of composite missile stabilizers is investigated. Two degrees of freedom (plunge and twist) analytical model of typical fin stabilizer airfoil section is presented. Based on this model the critical flutter speed for the composite missile stabilizer is derived for subsonic flight conditions. It was found that natural stabilizer frequencies (in bending and twisting) highly influence the maximum flutter speed. Natural fin frequencies (in bending and twisting) are calculated using finite element approach based on Lanczos method of frequencies extraction. Several modal frequency models are investigated and results are discussed, since the accurate prediction of natural frequencies plays significant role in overall flutter speed (VF) determination. For the trapezoidal stabilizer shape different laminate lay-up sequences are investigated, flutter speeds calculated and results compared in order to determine maximum flutter speed. The material of interest in this study was carbon based AS/4 - 3501-6..

1 Introduction

Aeroelastic phenomenon known as bending-torsion flutter is the coupled motion of lifting surface bending and twisting and rigid or flexible motion of the flight vehicle body. The “flutter” of missile stabilizers (fins) is a serious cause of stability loss and flight vehicle failure. It involves the unfavorable interaction of aerodynamic, elastic and inertia forces. The flexible missile structure, when subjected to high velocity flow, may experience flutter (Figure 1), in which the structural vibrations become unstable at a certain velocity [1].

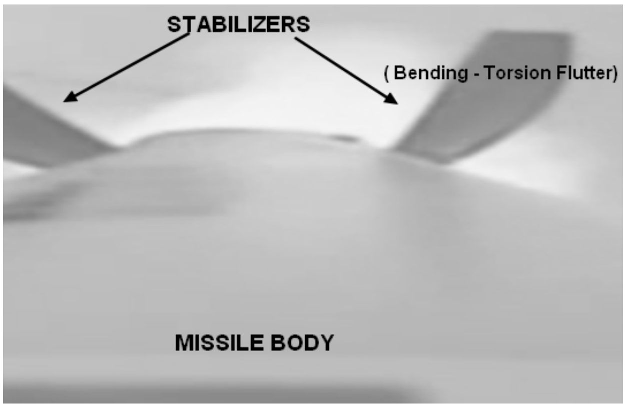

Figure 1. Missile fin flutter.

Flutter in missiles is affected mainly by the structural and aerodynamic properties of the fins and the mechanical properties of the actuators, whereas the missile body usually has a minor role. It is of paramount importance to design the fins and their actuators such that the flutter will not occur in the flight envelope.

In the present paper the flutter phenomenon on thin missile composite trapezoidal fins is investigated in quasi steady flow is investigated, with the objective to define the relation for flutter speed as a function of flight conditions, stabilizer geometry and material characteristics [2].

2 Composite Trapezoidal Fin 2D Flutter Model

A typical missile trapezoidal fin is presented in Figure 2. Consider a system consisting of a spring supported rigid fin airfoil. where airfoil is trapezoidal fin section lactated at approx. 70% of fin span. The system analyzed is presented in Figure 3.

If the airfoil is permitted to execute small vertical and angular displacements, it is convenient to describe the airfoil motion in generalized coordinates h and α. Expressed in generalized coordinates chosen, the fin displacement w, for any point along the fin chord (x) is:

$$w = -h - x \cdot \alpha \tag{1}$$

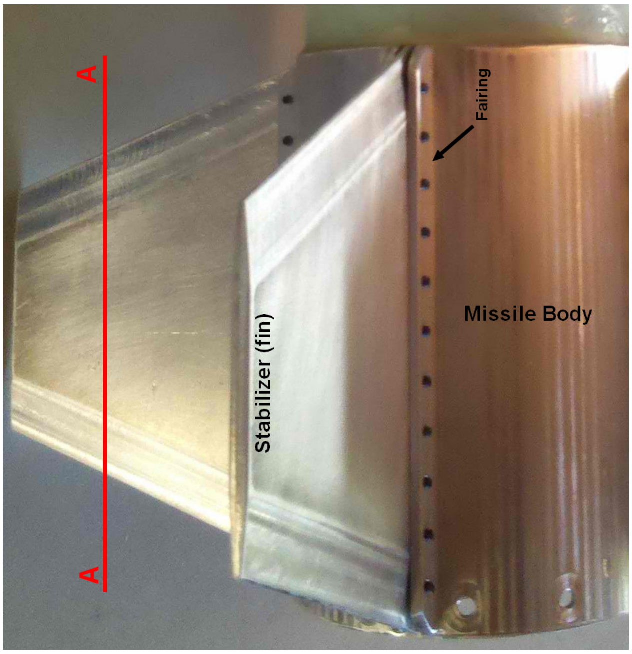

Figure 2. Missile trapezoidal fin analyzed airfoil location.

Writing the kinetic and strain energy equations for the fin spring system shown, and applying Lagrange's equations applied to this problem and assuming that for fin airfoils the center of gravity and shear center reside along spanwise line located at the midchord, the equations of motion associated are given as follows:

$$\begin{aligned} m\ddot{h} + K_h h &= -L \\ I_\alpha \ddot{\alpha} + K_\alpha \alpha &= M_y \end{aligned} \tag{2}$$

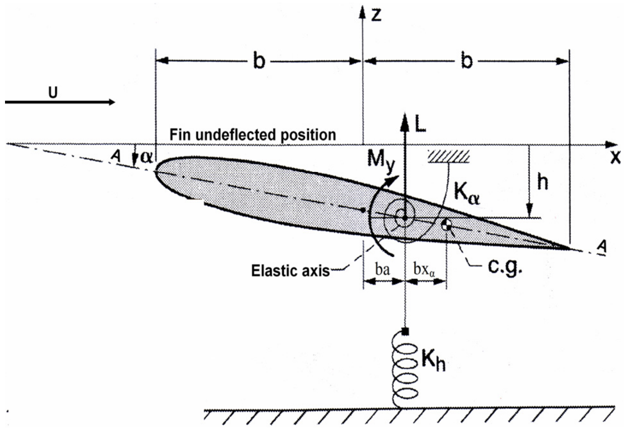

Figure 3. 2D fin flutter model.

where, m is spanwise fin mass, K_h spanwise bending stiffness, I_α is mass moment of inertia about fin mid chord line and K_α is spanwise torsional stiffness.

Analyzing the system of differential equations (Eq. 2), it is obvious that the flutter solution will depend on fin inertia properties and aerodynamic expressions for the lift and aerodynamic moment [3-5].

Applicable aerodynamic theories for fin flutter analysis are summarized in Table 1.

Table 1: Applicable aerodynamic theories in fin flutter analysis

	Aerodynamic theory			
	Dublet lattice Panel	Lifting Body	Strip theory	Piston theory
Mach number	Subsonic	Subsonic	Subsonic, Transonic, Supersonic	High Supersonic

Flow around trapezoidal fin is very complex [6]. To accurately predict pressures and speeds on a trapezoidal fin in flight tests in wind tunnels or CFD analysis has to be preformed (Figure 4).

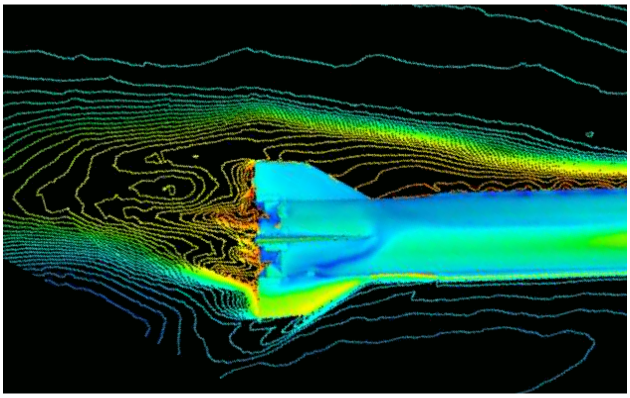

Figure 4. Air flow around trapezoidal missile fin.

The choice of particular aerodynamic theory depends on the Mach - number range in which flutter is expected to occur. That the phase angle between the normal force and angle-of attack is negligible, normal force due to the plunging motion is negligible, the unsteady pitching moment about the aerodynamic centre is negligible, that the fin aspect ratio is small and the amplitude of fin vibration is sufficiently small to allow for a linear approximation of the lift-curve slope the relations for quasi-steady aerodynamics can be used for the aerodynamic lift force and aerodynamic moment to calculate the fin flutter speed (V_F). Based on these approximations the equations of motion (Eq.2) become:

$$\begin{aligned} m\ddot{h} + K_h h &= -C_L \alpha \rho U^2 b \\ I_\alpha \ddot{\alpha} + K_\alpha \alpha &= C_L \alpha \rho U^2 x_a b^2 \end{aligned} \tag{3}$$

In the present investigation the harmonic motion is assumed:

$$\begin{aligned} h &= \bar{h} \cdot \sin(\omega t), \\ \alpha &= \bar{\alpha} \cdot \sin(\omega t) \end{aligned} \tag{4}$$

where $\bar{h}, \bar{\alpha}$ denote eigenvectors in fin plunging and twisting respectively, and ω is the frequency of coupled motion. Further, before obtaining the characteristic equation in, it is convenient to introduce the following substitutions:

$$\begin{aligned} &\omega_h^2 = \frac{K_h}{m},\ \omega_\alpha^2 = \frac{K_\alpha}{I_\alpha}, \\ &I_\alpha = \frac{mb^2 r_\alpha^2}{4},\ \mu = \frac{4m}{\pi \rho b^2} \end{aligned} \tag{5}$$

In relations (5) ω_h and ω_α are fin's natural frequencies in bending and twisting, r_α is the radius of gyration about the mid-chord and μ is dimensionless fin airfoil to airstreams mass ratio. After substituting the above substitutions and second derivatives of assumed harmonic motions into equations of motion the 4th order characteristic equation is obtained:

$$\begin{aligned} &\omega^4 + \omega^2 \left(\frac{8C_L U^2 x_a}{r_\alpha^2 \mu b^2 \pi} - \omega_h^2 - \omega_\alpha^2 \right) + \\ &+ \left(\omega_h^2 \cdot \omega_\alpha^2 - \frac{\omega_h^2 8 C_L U^2 x_a}{r_\alpha^2 \mu b^2 \pi} \right) = 0 \end{aligned} \tag{6}$$

There are four solutions to the above 4th order characteristic equation, however only two unique positive solutions of ω. One solution to the vibration frequency equation specific to this problem is the natural bending frequency.

The configuration is absent of a mass imbalance and the shear centre lies on the mid-chord coincident with the spanwise gravity distribution. Also damping has been excluded from the analysis. The solutions of equation 6 are:

$$\begin{aligned} &\omega_1 = \omega_h, \\ &\omega_2 = \sqrt{\frac{\left[\mu \pi \left(\omega_\alpha^2 r_\theta^2 \mu b^2 \pi - 8 C_L U^2 x_a \right) \right]}{b r_\theta \mu \pi}} \end{aligned} \tag{7}$$

By definition the flutter velocity is associated with the coalescence of the two frequencies into a single frequency. That is when $\omega_1 = \omega_2$. The coalescence of the two frequencies marks the boundary between damped and undamped vibration characterized by a neutrally stable oscillation. The flutter velocity is obtained as follows:

$$V_F = U(\omega_1 = \omega_2) = \sqrt{\frac{\pi b^2 r_\alpha^2 \mu \left(\omega_\alpha^2 - \omega_h^2 \right)}{8 C_L x_a}} \tag{8}$$

3 Estimation of the composite fin natural frequencies in bending and torsion

Based on the equation (8), required input for the flutter speed calculation include fin's natural frequencies of vibration in bending and torsion.

These frequencies can be determined experimentally or, as presented in the following text using numerical approach, as in this case finite element method.

The solution of the equation of motion for natural frequencies and normal modes requires a special reduced form of the equations of motion. If there is no damping and no applied loading, the equation of motion in matrix form reduces to:

$$[M]\{\ddot{u}\}+[K][u]=0 \tag{9}$$

where [M] is the mass matrix and [K] is the stiffness matrix. This is the equation of motion for undamped free vibration. To solve previous equation, harmonic solution is assumed in the following form:

$$\{u\}=\{\phi\}\sin\omega t \tag{10}$$

Where $\{\Phi\}$ are the mode shapes and ω is the circular natural frequency.

Plate elements, based on Kirchoff thin plate theory are used for modeling rocket body and the fin. The Finite element mesh is presented in the following picture (Figure 2).

The fin material used in this study was AS/4 – 3501-6 thin lamina (1.25 mm) with fiber volume fraction of 0.62. Material data relevant for modal analysis is given in Table2.

Mode shapes (bending and torsion) for the composite trapezoidal fin are presented in the following figures.

Table 2: composite fin material properties

AS4 / 3501-6				
density	E_1	E_2	G_{12}	ν_{12}
[g/cm3]	[GPa]	[GPa]	[GPa]	[-]
1.580	142	10.3	7.2	0.26

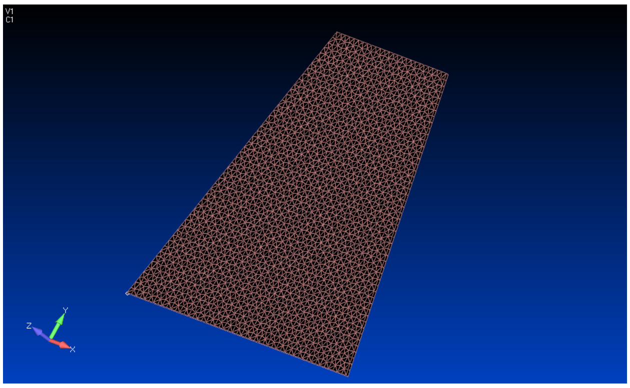

Figure 5. FEA model for modal analysis.

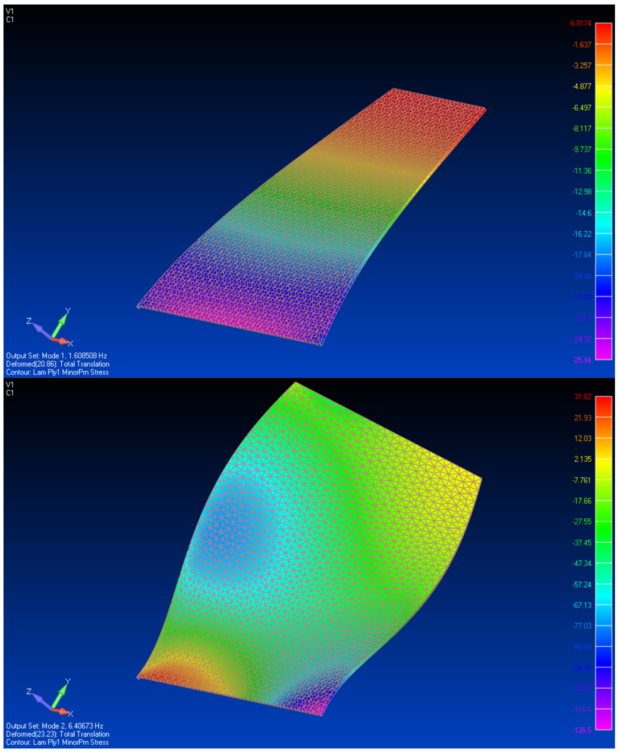

Figure 6. Composite fin mode shapes in bending and torsion.

Once natural frequencies are found, and based on the fin's geometry and material characteristic the c speed at which flutter should occur (quasi-steady flow) the equation (8) is used to determine the critical flutter speed (V_F).

In the present analysis the composite fin construction was considered as described before. The fin was constructed from two layers of AS4 carbon fibers embedded in the 3501-6 matrix. It was found that fiber orientation, of each lamina highly influences the values of bending and torsion natural frequencies and therefore has a high impact on the flutter speed (V_F) itself (see Eq 8.) [7-8].

Determining natural frequencies (torsion and bending) for different stack-up sequences (where each fiber angle, for each ply was in the range from 0^0 to 90^0 varied independently with the step of 15^0). By defining the squared difference of natural frequencies in torsion and bending (twist and plunge) as Δ

$$\Delta=\omega_\alpha^2-\omega_h^2 \tag{11}$$

The variation of Δ as a function of Θ_1 and Θ_2 (where Θ_1 is fiber orientation angle in respect to flight direction of the fin outer ply and Θ_2 is fiber orientation angle in respect to flight direction of the fin inner ply) is presented in the following figure (Figure 7).

Since in the fin design and in respect to flutter requirements it is always required to have flutter speed above the missile flight envelope the maximum of Δ function (Eq. 11) is sought. For the present fin design, materials used and most importantly the fiber orientation, the value of Δ=2190 peaks for $\Theta_1=15^0$ and $\Theta_1=30^0$ which represents the optimal stack-up sequence, since for this fiber orientation the flutter speed is maximal.

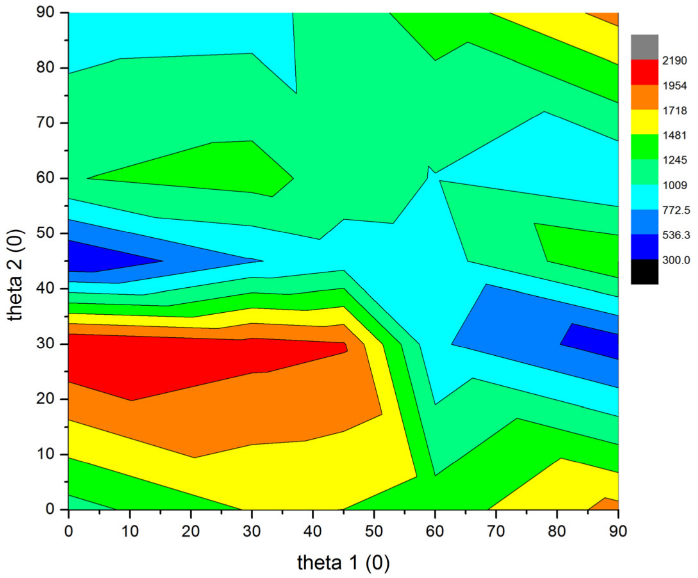

Figure 7. Natural frequencies (squared difference) as a function of fiber orientation for two layer composite fin.

4 Conclusions

In the present work the flutter analysis of missile trapezoidal fins is analyzed. For the subsonic flight conditions and based on 2D flutter model the relation for flutter speed (V_F) is derived and presented.

Using numerical approach, modal analysis on trapezoidal composite fin was performed. Several extraction algorithms were analyzed and it was found that the Lanczos method renders best results in respect to solution accuracy and computational cost.

Fiber orientation of the composite fin has very high influence on the fin natural frequencies and therefore the flutter speed itself. Therefore, the special attention has to be given to composite design when composite fins are considered as missile stabilizers.

References

[1] NASA Aeroelasticity Handbook, Volume 2: Design Guides, NASA/TP—2006-212490/VOL2/PART2.

[2] John A.C. Kentfield.: Aircraft with outboard horizontal stabilizers, history, current status, development potential, Progress in Aerospace Sciences, Progress in Aerospace Sciences,45,2009..

[3] M. Petrolo, Flutter analysis of composite lifting surfaces by the 1D Carrera Unified Formulation and the doublet lattice method, Composite Structures, Volume 95, January 2013, Pages 539-546.

[4] Jong-Won Lee, Jun-Seong Lee, Jae-Hung Han, Hyung-Ki Shin, Aeroelastic analysis of wind turbine blades based on modified strip theory, Journal of Wind Engineering and Industrial Aerodynamics, Volume 110, November 2012, Pages 62-69.

[5] Zhichun Yang, Jian Zhou, Yingsong Gu, Integrated analysis on static/dynamic aeroelasticity of curved panels based on a modified local piston theory, Journal of Sound and Vibration, In Press, Corrected Proof, Available online 17 July 2014.

[6] A. Attorni, L. Cavagna, G. Quaranta, Aircraft T-tail flutter predictions using computational fluid dynamics, Journal of Fluids and Structures, Volume 27, Issue 2, February 2011, Pages 161-174.

[7] Guo, S.J; Bannerjee, J.R.; Cheung, C.W.: The effect of laminate lay-up on the flutter speed of composite wings, Journal of Aerospace Engineering, Vol. 217, No 3, 2003, pp. 115-122

[8] Jinqiang Li, Yoshihiro Narita, Multi-objective design for aeroelastic flutter of laminated shallow shells under variable flow angles, Composite Structures, Volume 111, May 2014, Pages 530-539.

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